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K 中間子束縛状態における ハイペロン混在の効果

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1. Introduction

Multi-strangeness system in hadronic matter

中性子星内部の高密度物質

hyperonic matter — Strange matter

(Λ, Σ, Ξ, ・・・ in the ground state)

Kaon condensation

(u, d, s quark matter)

実験で得られる高密度物質

Strangeness-conserving system

Kaonic nuclei

(bound state of K^- meson)

[Y. Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.]
[A. Dote, H. Horiuchi et al., Phys. Lett. B 590 (2004) 51; Phys.Rev. C70 (2004) 044313.]

|S| = 0, 1, 2, 3, ・・

Multi-Antikaonic Nuclei (MKN)

relativistic mean-field theory (RMF)
[T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]

- central region: high density $\rho_B \sim 3.5\ \rho_0$

Meson-exchange models (MEM)
[c.f. D. Gazda, E. Friedman, A. Gal, J. Mares, Phys. Rev. C76, 055204 (2007); Phys. Rev. C77, 045206 (2008).]

ストレンジネス数の増加によるK中間子ダイナミクスの変化

⇕

中性子星物質中でのK凝縮との関係

Multi-Antikaonic Nuclei (MKN) に対する hyperon -mixing effects

(Coexistence of antikaons and hyperons)

[T. Muto, Phys. Rev. C 77 (2008) 015810; Nucl. Phys. A804 (2008) 322.]

(in the liquid drop picture)

- Considerable softening of the EOS

Nucleon-nucleon repulsion is avoided at high densities.
[c.f. S. Nishizaki, Y. Yamamoto, T. Takatsuka, Prog. Theor. Phys.108(2002)703.]
Kaon-baryon attractive interactions get stronger.

} due to hyperon-mixing

- At high densities, stiffness of the EOS is recovered due to repulsive interaction between baryons

→ A local energy minimum => highly dense self-bound object

--- decaying only through weak processes

↕

[D. Gazda, E. Friedman, A. Gal, J. Mares, Phys. Rev. C 80, 035205 (2009).]

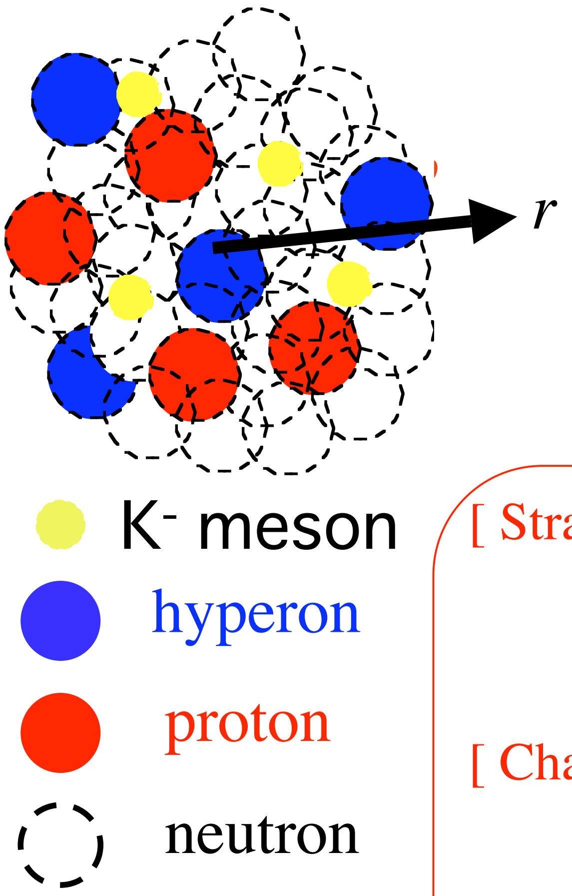
→ 非一様密度分布など原子核の有限性を現実的に取り入れた枠組みが必要。

相対論的平均場理論（ＲＭＦ）によるＫ凝縮ハイパー核の可能性の検討

2. Formulation

2-1 Outline of Kaon-condensed hypernuclei

Multi-$\bar{K}$ Nuclei



[Initial target nucleus]

$A = N + Z$: mass number

Z: the number of proton

$|S|$: the number of the embedded K^-

Assume : Spherical symmetry

Local density approximation for baryons (p, n, Λ, Σ^-)

[Strangeness conservation]

$$\int d^3r \, (\rho_{K^-}(r) + \rho_\Lambda(r) + \rho_{\Sigma^-}(r)) = |S|$$

[Charge conservation]

$$\int d^3r \, (\rho_p(r) - \rho_{K^-}(r) - \rho_{\Sigma^-}(r)) = Z - |S|$$

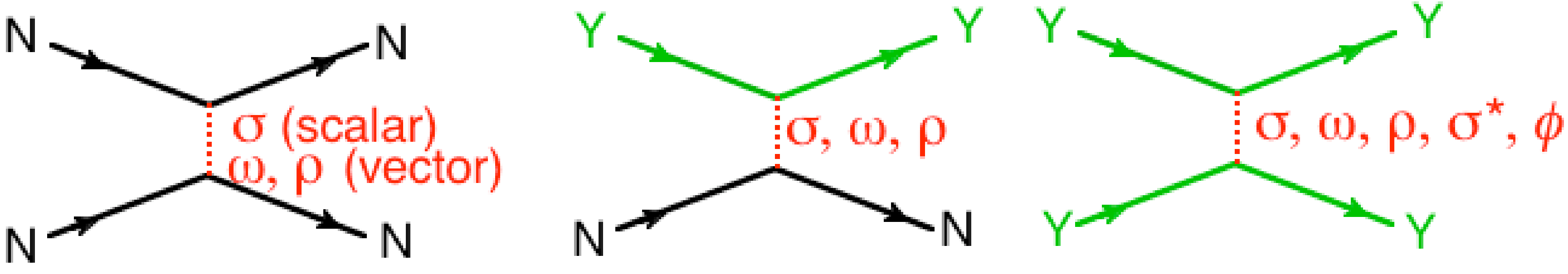
[Baryon number conservation]

$$\int d^3r \, (\rho_p(r) + \rho_n(r) + \rho_\Lambda(r) + \rho_{\Sigma^-}(r)) = A$$

2-2 Relativistic Mean-Field (RMF) theory

N-N (N = p, n)

Y-N, Y-Y ($Y = \Lambda, \Sigma^-$)



$\sigma^* \sim \bar{s}s$

$\phi \sim \bar{s}\gamma s$

Nonlinear chiral effective Lagrangian

$\bar{K} - N, \bar{K} - \bar{K}$ interactions

[D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175 (1986) 57.]

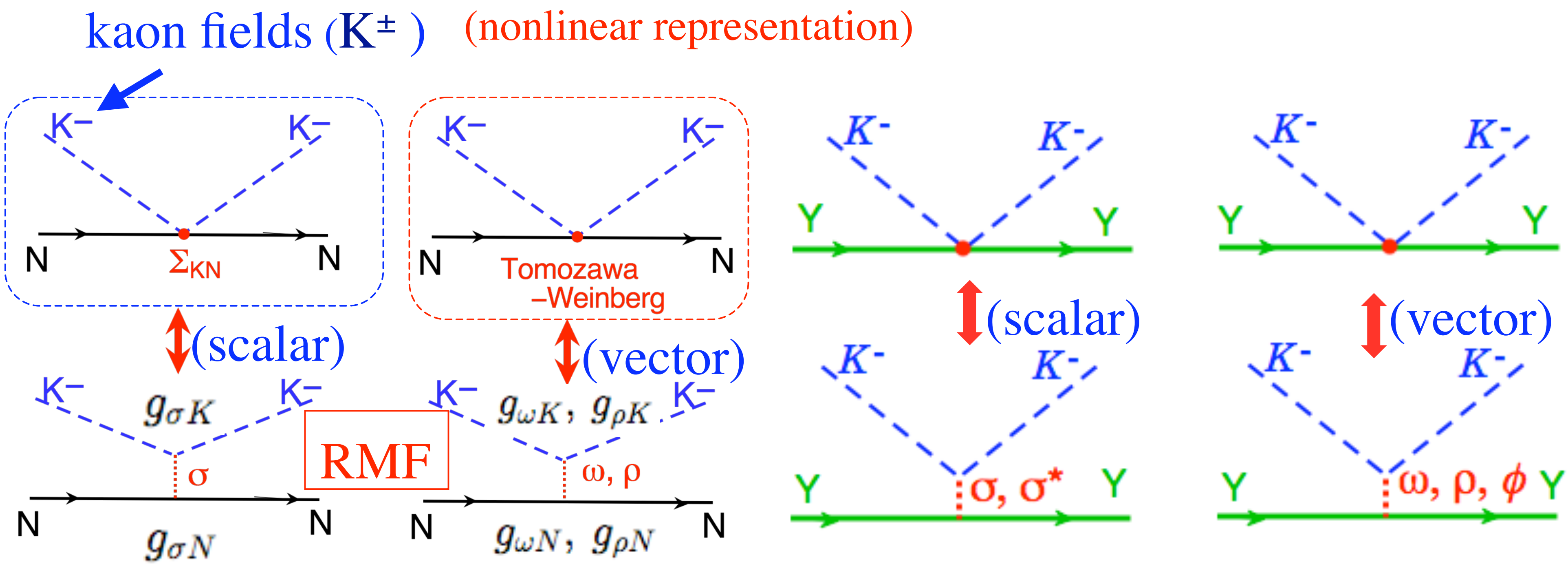
Meson fields ($K^\pm$) (nonlinear representation)

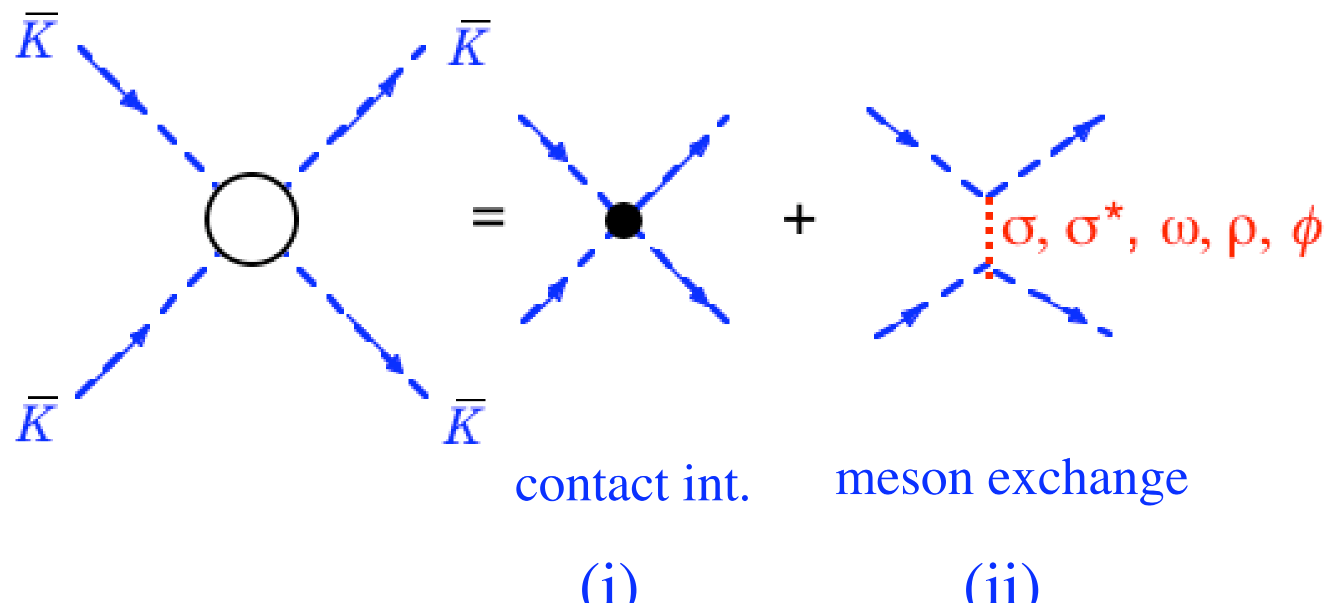
$$\Sigma \equiv e^{2i\Pi/f} \qquad \Pi = \pi_a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & K^+ \\ 0 & 0 & 0 \\ K^- & 0 & 0 \end{pmatrix}$$

Condensate assumption

(K^- mesons are condensed in the lowest energy state)

$$\langle K^- \rangle = \frac{f}{\sqrt{2}} \theta(\mathbf{r}) \qquad f = \mathbf{93\ MeV}$$


kaon fields (K±)
(nonlinear representation)
K−
K−
N
ΣKN
N
Tomozawa
–Weinberg
(scalar)
(vector)
gσK
gωK , gρK
gσN
gωN , gρN
σ
ω, ρ
RMF
K-
Y
σ, σ*
ω, ρ, φ


K̄
σ, σ*, ω, ρ, φ
contact int.
meson exchange
(i)
(ii)

2-3 Equations of motion for meson fields

(coherent state)

$\delta\Omega/\delta\theta(r) = 0$ K⁻ field equation

・nonlinear $\bar{K}$-$\bar{K}$ int.

$$\langle K^-\rangle = \frac{f}{\sqrt{2}}\theta(\mathbf{r})$$

$$\widetilde{\omega}_{K^-} = \omega_{K^-} - V_{\rm Coul}$$

$$\nabla^2\theta = \sin\theta\Big[\Big(m_K^2 - 2g_{\sigma K}m_K\sigma - 2g_{\sigma^* K}m_K\sigma^*\Big) - 2\widetilde{\omega}_{K^-}(g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0) - \widetilde{\omega}_{K^-}^2\cos\theta\Big]$$

$$-\nabla^2\sigma + m_\sigma^2\sigma = -\frac{dU}{d\sigma} + g_{\sigma N}(\rho_n^s + \rho_p^s) + g_{\sigma\Lambda}\rho_\Lambda^s + g_{\sigma\Sigma^-}\rho_{\Sigma^-}^s + 2f^2 g_{\sigma K}m_K(1-\cos\theta)$$

$$-\nabla^2\omega_0 + m_\omega^2\omega_0 = g_{\omega N}(\rho_n + \rho_p) + g_{\omega\Lambda}\rho_\Lambda + g_{\omega\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\omega K}\widetilde{\omega}_K(1-\cos\theta)$$

$$-\nabla^2 R_0 + m_\rho^2 R_0 = g_{\rho N}(\rho_p - \rho_n) + g_{\rho\Lambda}\rho_\Lambda - g_{\rho\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\rho K}\widetilde{\omega}_K(1-\cos\theta)$$

$$-\nabla^2\sigma^* + m_\sigma^2\sigma^* = g_{\sigma^*\Lambda}\rho_\Lambda^s + g_{\sigma^*\Sigma^-}\rho_{\Sigma^-}^s + 2f^2 g_{\sigma^* K}m_K(1-\cos\theta)$$

$$-\nabla^2\phi_0 + m_\phi^2\phi_0 = g_{\phi\Lambda}\rho_\Lambda + g_{\phi\Sigma^-}\rho_{\Sigma^-} - 2f^2 g_{\phi K}\widetilde{\omega}_K(1-\cos\theta)$$

$$\nabla^2 V_{\rm Coul} = 4\pi e^2(\rho_p - \rho_{\Sigma^-} - \rho_{K^-})$$

2-4 Choice of parameters

--- NN interaction ---

Reproduce gross features of normal nuclei and nuclear matter

- saturation properties of nuclear matter (ρ_0 =0.153 fm^{-3})
- binding energy of nuclei and proton-mixing ratio
- density distributions of p and n

$g_{\sigma N}$ $g_{\omega N}$, $g_{\rho N}$

--- vector meson couplings for Y --- SU(6) symmetry

$$g_{\omega\Lambda} = g_{\omega\Sigma^-} = \frac{2}{3} g_{\omega N} \qquad g_{\rho\Lambda} = 0\ ,\ g_{\rho\Sigma^-} = 4 g_{\rho N} \qquad g_{\phi\Lambda} = g_{\phi\Sigma^-} = -\frac{\sqrt{2}}{3} g_{\omega N}$$

--- scalar meson couplings for Y --- ハイパー核実験

$$U_\Lambda^N(\rho_0) = -g_{\sigma\Lambda}\sigma + g_{\omega\Lambda}\omega_0 = -27\ \text{MeV}$$

[D. J. Millener, C. B. Dover and A. Gal, Phys. Rev. C38 (1998), 22700.]

$$g_{\sigma\Lambda} = 3.84$$

$$U_{\Sigma^-}^N(\rho_0) = -g_{\sigma\Sigma^-}\sigma + g_{\omega\Sigma^-}\omega_0 = 23.5\ \text{MeV}$$

repulsive case

$$g_{\sigma\Sigma^-} = 2.28$$

[J. Dabrowski, Phys. Rev. C60 (1999), 025205.]

(K^-, $\pi^\pm$) at BNL, (π, K^+) at KEK

$$g_{\sigma^* N} = g_{\sigma^*\Lambda} = g_{\sigma^*\Sigma^-} = 0$$

--- vector meson couplings for Kaon ---

$g_{\omega K} = g_{\omega N}/3 \quad g_{\rho K} = g_{\rho N}$ ← quark and isospin counting rule

$g_{\phi K} = 6.04/\sqrt{2}$

--- scalar meson couplings for Kaon ---

$g_{\sigma K}$ ← $U_K = -(g_{\sigma K}\sigma + g_{\omega K}\omega_0)$ at ρ_0 in symmetric nuclear matter

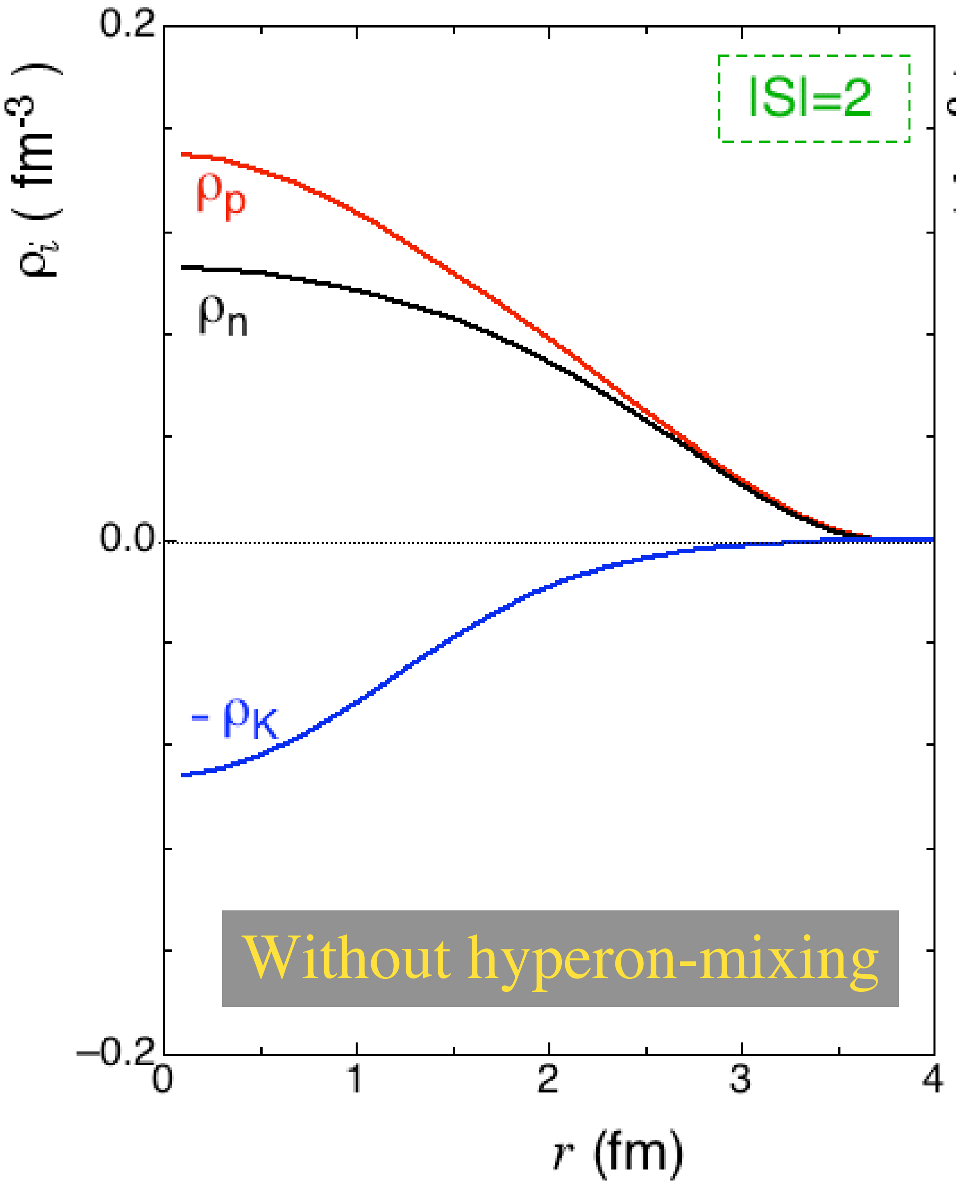
$U_K = -80$ MeV ($\Sigma_{KN} \sim 330$ MeV)

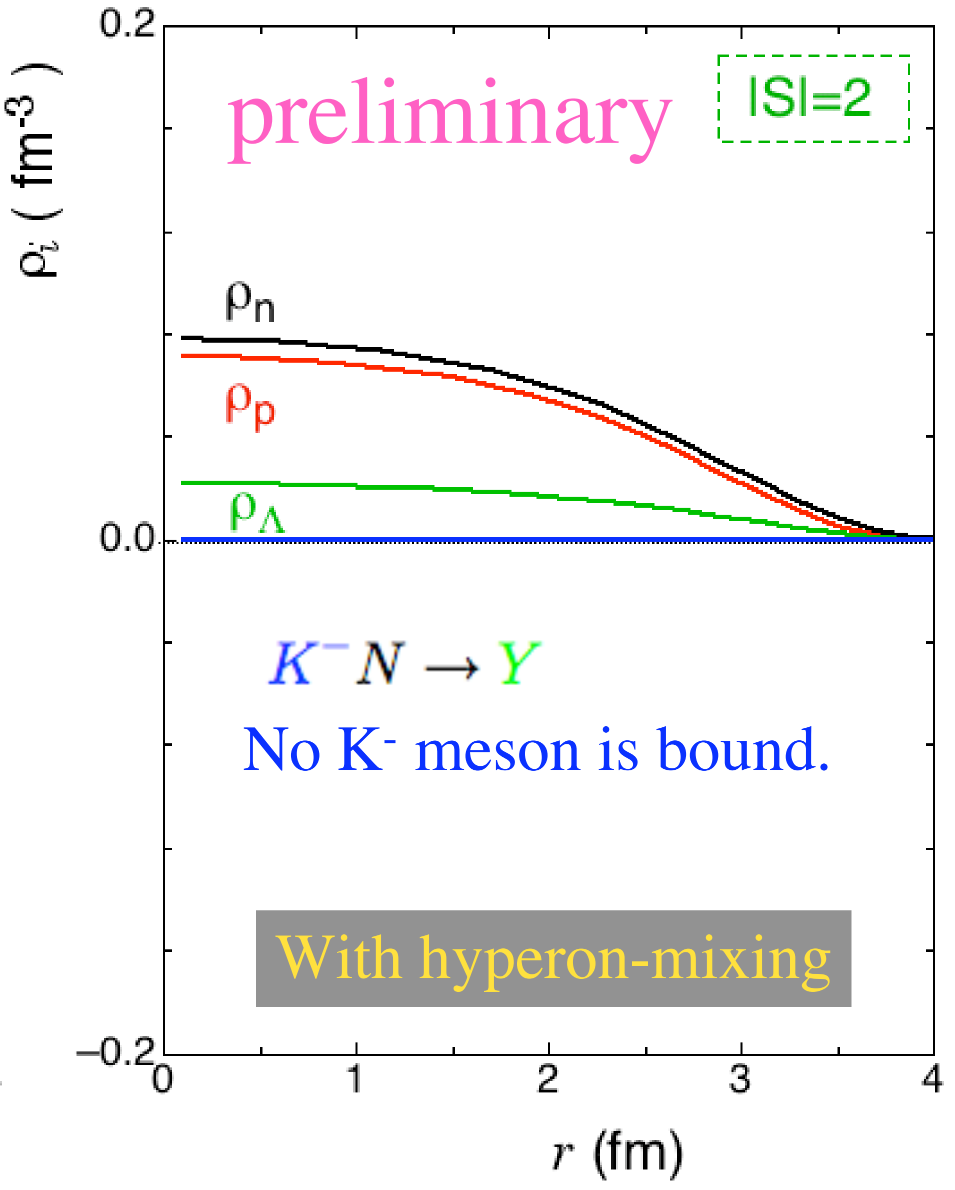
$g_{\sigma^* K} = 2.65$ ← Decay of $f_0(975)$

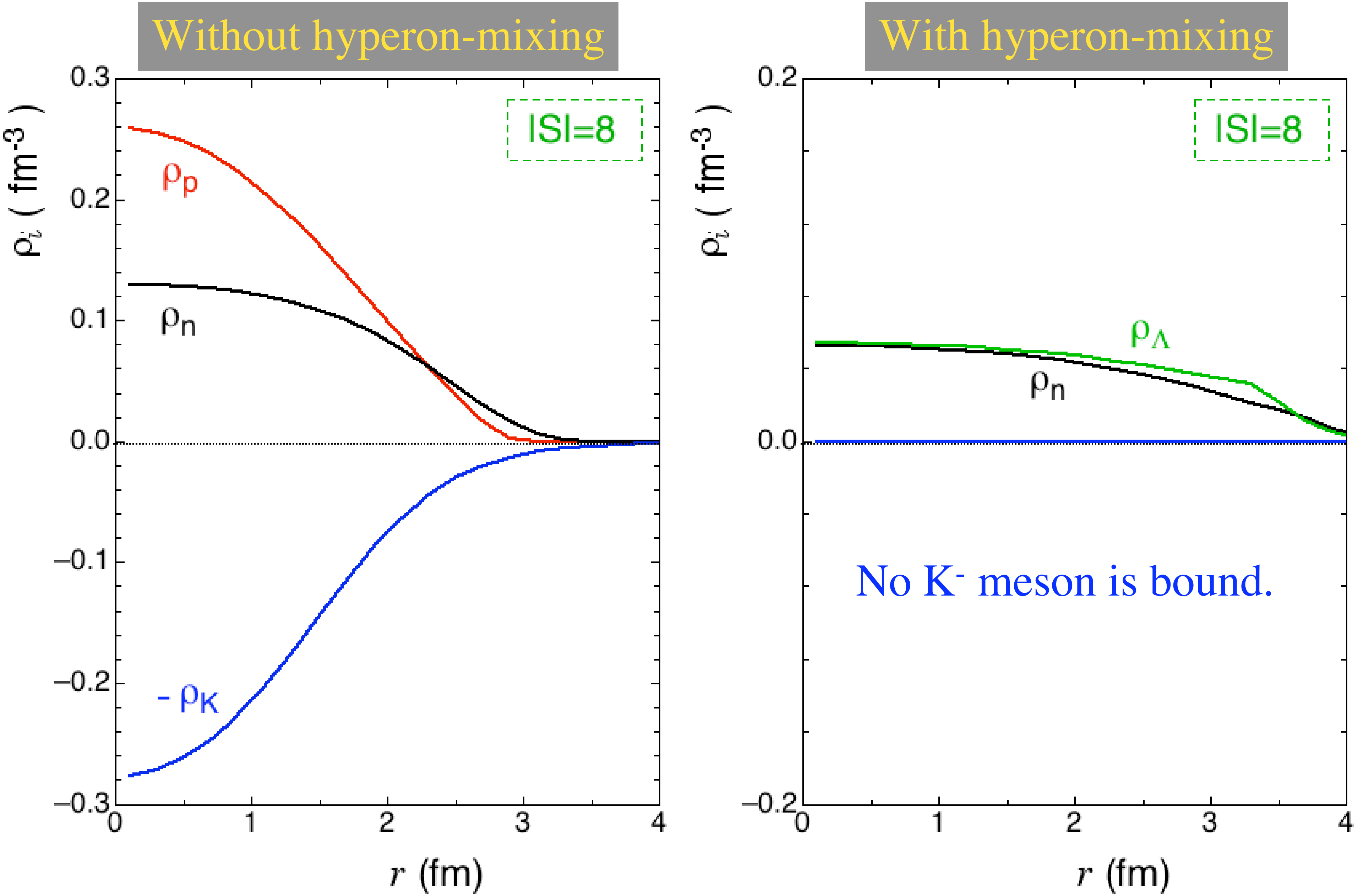
3. Numerical results   3-1 density distributions

A=15, Z=8 ($^{15}_{8}O$)

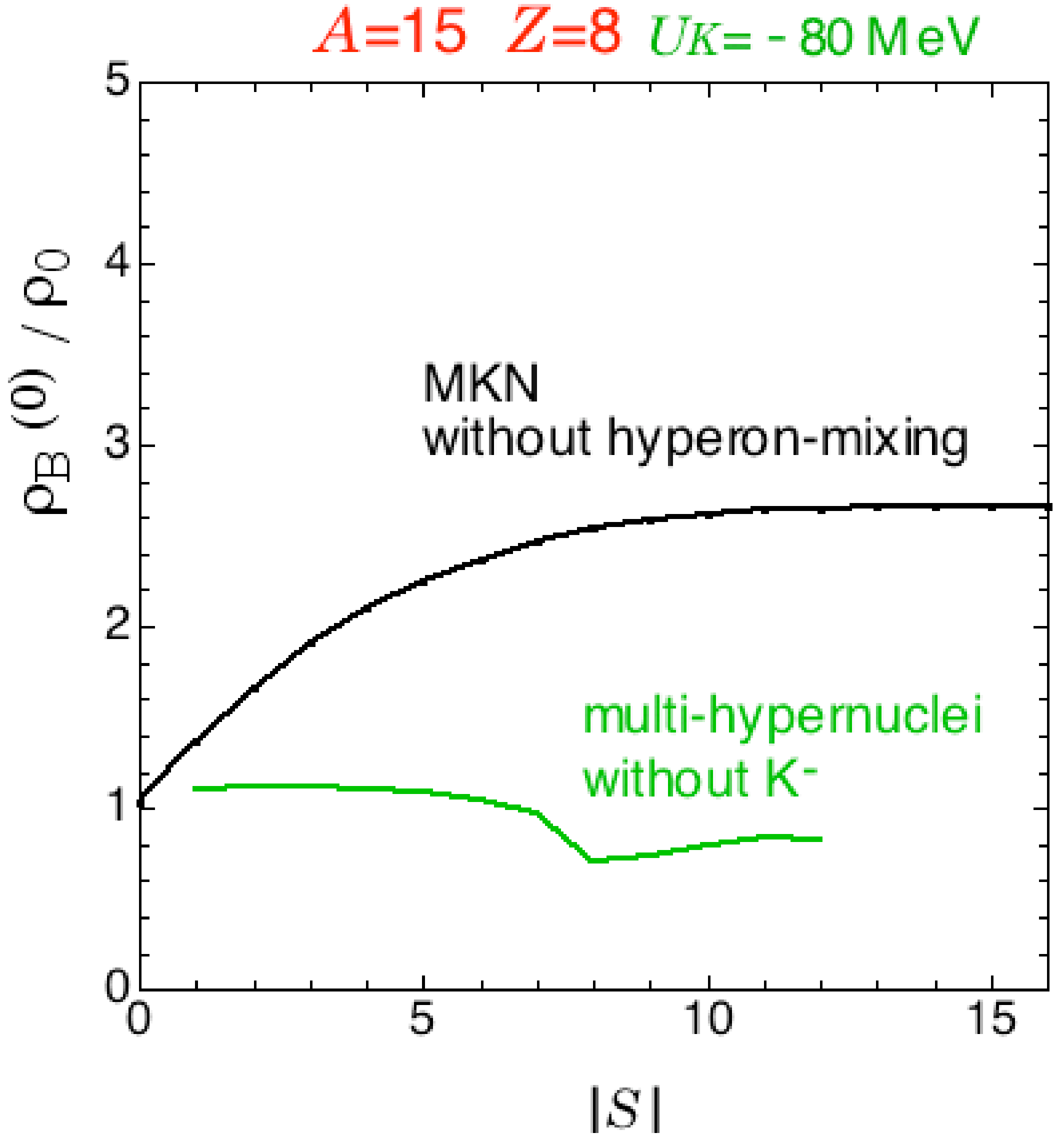
U_K= - 80 MeV






Without hyperon-mixing
With hyperon-mixing
|S|=8
|S|=8
ρ_p
ρ_n
$-\rho_K$
ρ_Λ
ρ_n
ρ_i (fm^{-3})
r (fm)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0
1
2
3
4
No K$^-$ meson is bound.

3-2 |S|-dependence of central density $\rho_B^{(0)}$



Central region

MKNの場合

K- mesons と protons が
強い引力で中心に引かれる。

$\rho_B^{(0)} \sim 2.6\ \rho_0$ for large |S|

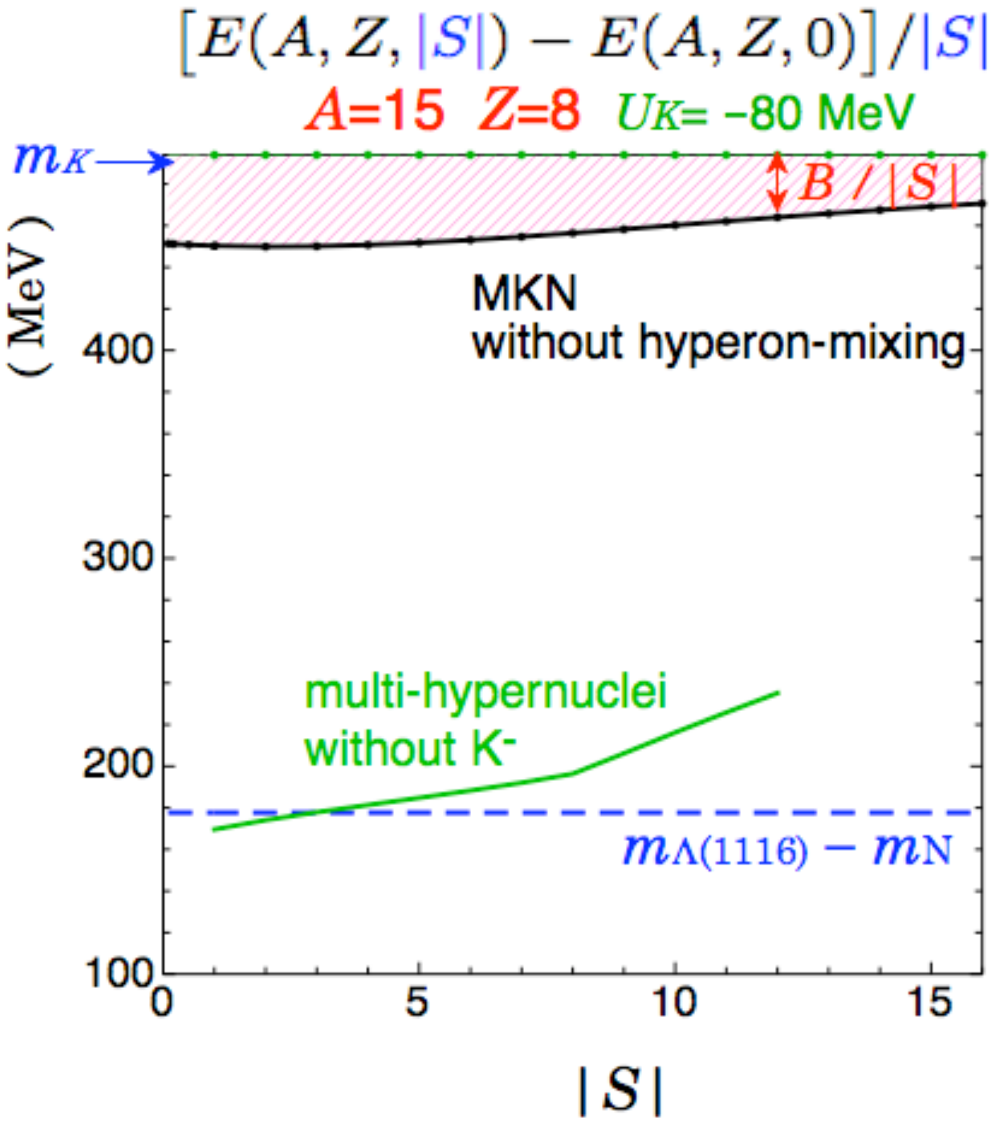
Multi-hypernucleiの場合

$\rho_B^{(0)} \sim \rho_0$

3-3 Stability of the multi-strangeness nuclei

Total energy of the MKN

Binding energy : $-B(A, Z, |S|) = E(A, Z, |S|) - \left[E(A, Z, 0) + |S| \cdot m_K\right]$



$$m_{K^-} - B/|S| > m_{\Lambda(1116)} - m_N$$

$\Rightarrow$ $K^- NN \to \Lambda(1116) N$

Strong decay of the MKN

4. 中性子星内部のK中間子凝縮との関係

実験室系

$\omega_{K^-} = 400 \sim 450$ MeV $> \mu_\Lambda - \mu_p$ ← 原子核の有限性

Chemical equilibrium for strong processes

$K^- p \rightleftharpoons \Lambda, \quad K^- \Lambda \rightleftharpoons \Xi^-, \quad K^- n \rightleftharpoons \Sigma^-$

満たしにくい

↕

中性子星内部 無限系

chemical equilibrium for weak processes

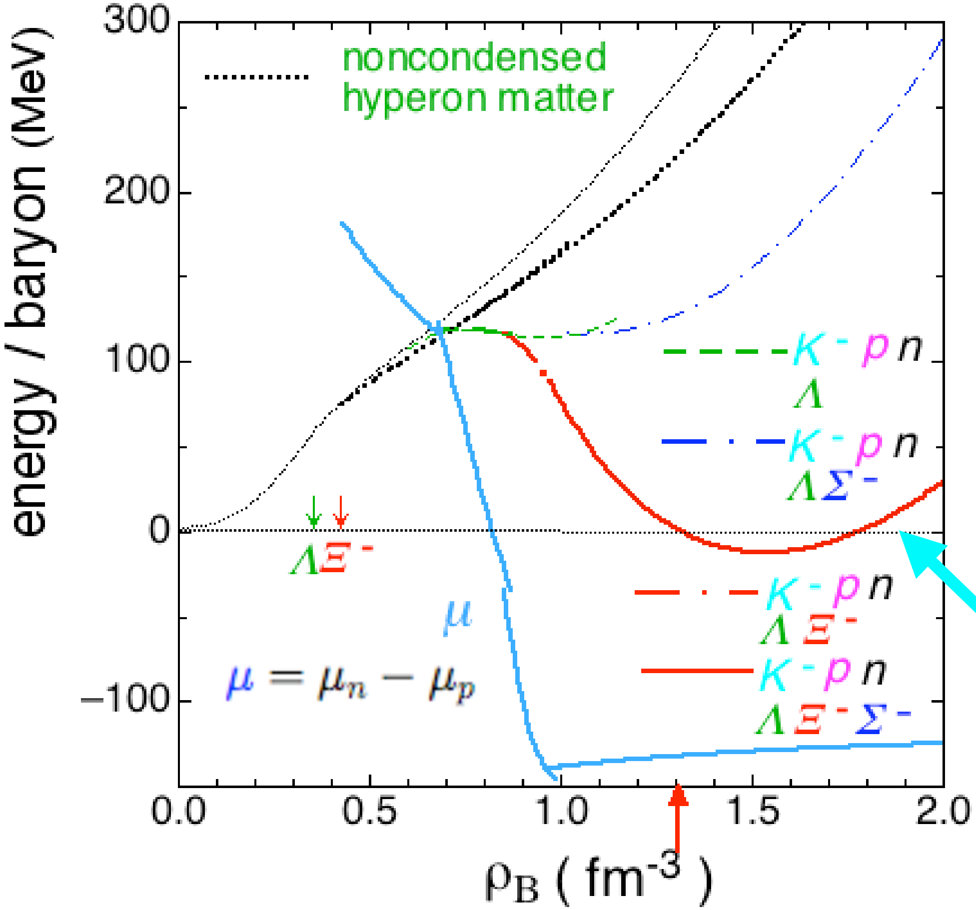
$n \rightleftharpoons p\, K^- \qquad p\, e^- \rightleftharpoons \Lambda\ (\nu_e) \qquad n\, e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

$n \rightleftharpoons p\, e^-\ (\bar{\nu}_e) \qquad \Lambda\, e^- \rightleftharpoons \Xi^-\ (\nu_e)$

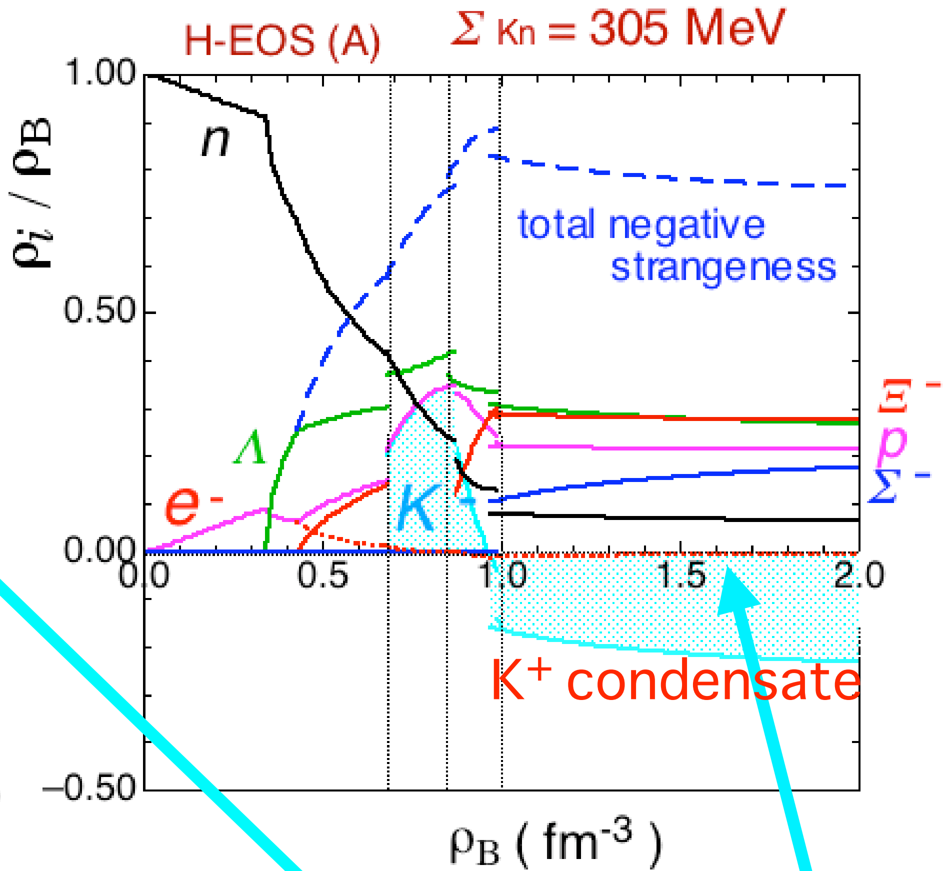
K^- chemical potential : $\omega_{K^-} = \mu = \mu_n - \mu_p < 0$ for high densities

--- including Ξ^- ---

Energy / baryon (ε / ρ_B)



Particle fraction



$$\mu^2\cos\theta - m_K^2 + \frac{1}{f^2}\sum_{i=p,\Lambda,\Xi^-,n,\Sigma^-}\rho_i^s\cdot\Sigma_{Ki} + \frac{\mu}{f^2}\left(\rho_p + \frac{1}{2}\rho_n - \rho_{\Xi^-} - \frac{1}{2}\rho_{\Sigma^-}\right) = 0$$

K⁻ density :

$$\rho_{K^-} = \mu f^2 \sin^2\theta + \left(\rho_p + \frac{1}{2}\rho_n - \rho_{\Xi^-} - \frac{1}{2}\rho_{\Sigma^-}\right)(1-\cos\theta) < 0$$

free part

K⁻B vector int.

5. Summary and outlook

相対論的平均場理論と$\bar{K}$ -B,$\bar{K}$ - $\bar{K}$ 相互作用に対する非線形 chiral Lagrangianの枠組みで, K^- 中間子とハイペロンの共存した原子核の存在可能性を検討した。

原子核の有限性のため, K^- 中間子がバリオンから受ける引力が無限系（中性子星内部）の場合ほど大きくなく, K^- の lowest energy が $\omega_{K^-} \sim 400$ MeV よりも低くならない。

➡ $K^- N \rightarrow Y$ を通じて, 初めK- 中間子が担っていたストレンジネスがすべてハイペロン(Y)に吸収される。

中心核密度 $\rho_B^{(0)} \sim \rho_0$

Outlook

Role of hyperons (Y)

- Ξ^- -mixing の効果
- inelastic channel coupling effects (kaon decay width . . .)

$$\bar{K}N \to \pi\Lambda, \pi\Sigma$$

- Role of P-wave KNY interactions

Quasi-baryons

$$|\widetilde{\Lambda}_\pm\rangle = \cos\phi \cdot |\Lambda_{\pm 1/2}\rangle \pm i \sin\phi \cdot |p_{\pm 1/2}\rangle$$

$$|\widetilde{n}_\pm\rangle = \cos\phi' \cdot |n_{\pm 1/2}\rangle \pm i \sin\phi' \cdot |\Sigma^-_{\pm 1/2}\rangle$$

- Realistic framework beyond the local density approximation for baryons